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SEISMIC POTENTIAL ASSOCIATED WITH SUBDUCTION IN THE NORTHWESTERN UNITED STATES

BY THOMAS H. HEATON AND HIROO KANAMORI

ABSTRACT

Despite good evidence of present-day convergence of the Juan de Fuca and North American plates, there has been remarkably little historical seismic activity along the shallow part of the Juan de Fuca subduction zone. Although we cannot completely rule out the possibility that the plate motion is being accommodated by aseismic creep, we find that the Juan de Fuca subduction zone shares many features with other subduction zones that have experienced great earthquakes.

INTRODUCTION

In this paper, we compare the mode of subduction of the Juan de Fuca plate beneath the North American plate with that of other subduction zones. We show that the Juan de Fuca subduction zone shares many features with other subduction zones that experience great earthquakes, while several features indicative of aseismic subduction are absent. General reviews of characteristics of the subduction process are given by Kanamori (1977a), Uyeda and Kanamori (1979), Ruff and Kanamori (1980), and Lay *et al.* (1982). They demonstrate the existence of striking correlations between the nature of seismic energy release and the physical characteristics of subduction zones. In general, they find that total seismic energy release rates are highest along subduction zones where young oceanic crust is subducted rapidly. They interpret this result to be a systematic variation in seismic coupling which is related to buoyancy of the subducted lithosphere.

We begin by summarizing the results of the studies mentioned above. We then discuss the physical characteristics of the Juan de Fuca subduction zone, describe some of the similarities between it and other subduction zones, and make some inferences about the expected seismic potential of the area.

SEISMIC COUPLING AND EARTHQUAKE SIZE

Kanamori (1977a) points out that the seismic energy release rate along subduction zones is not a simple linear function of convergence rates. Ruff and Kanamori (1980) show that the seismic energy release rate is closely related to the size of the maximum observed earthquake along any subduction zone. That is, the cumulative energy release from small events is usually negligible compared to the energy released by the largest events in a region. Kanamori (1977b) shows that, on a world-wide basis, the cumulative seismic energy release rate is closely related to the occurrence of very large earthquakes. It follows that the seismic energy release rate along individual subduction zones is closely related to the size of the maximum earthquake observed along that zone. In general, shallow low-angle thrust events are the dominant factor in determining seismic energy release rates.

Kanamori (1977a) concludes that variations in the seismic energy release rates (i.e., size of maximum earthquake) for differing subduction zones are caused by differences in seismic coupling. Strong seismic coupling implies that slip occurs only during earthquakes, whereas weak seismic coupling implies that slip occurs mainly in the form of aseismic creep.

Seismic Coupling and Subduction Zones

We now summarize the results of Kanamori (1977a), Uyeda and Kanamori (1979), Ruff and Kanamori (1980), and Lay *et al.* (1982), who correlated physical characteristics of the subduction process with the maximum earthquake size for most of the major subduction zones. As was just discussed, this correlation is interpreted in terms of seismic coupling, which is related to the buoyancy of the subducted lithosphere. The following features seem well correlated with observed maximum earthquake size.

Convergence rate and age of subducted lithosphere. In Figure 1, we show the

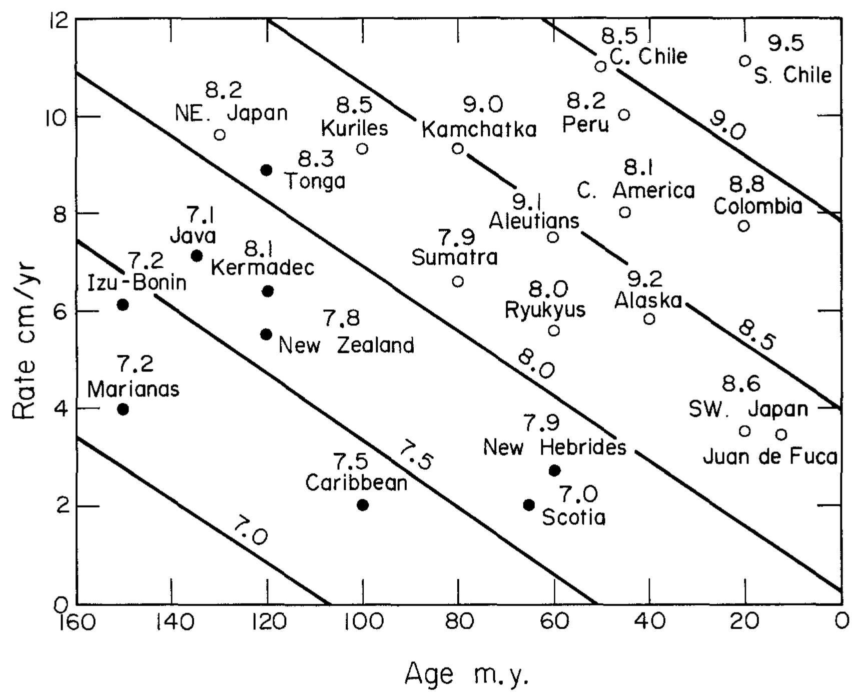

FIG. 1. Relation of maximum energy magnitude, M_w, to convergence rate and age of subducted lithosphere for major subduction zones. The contours of M_w are the predicted maximum earthquake magnitudes resulting from linear regression of observed maximum earthquake magnitude against the other two variables. Dots and circles are subduction zones with and without active back-arc basins, respectively (modified from Ruff and Kanamori, 1980).

relation between the maximum observed energy magnitude, M_w, and the convergence rate and age of subducted lithosphere for the major subduction zones. Ruff and Kanamori (1980) performed a linear regression of convergence rate and lithospheric age against the maximum observed moment magnitude, and the solid diagonal lines represent the best linear least-squares fit. It is clear that the maximum observed earthquake size increases with increasing convergence rate and decreasing lithospheric age. In Figure 2, we show this same correlation. In this figure, however, the observed maximum energy magnitude is plotted against the energy magnitude predicted from the regression analysis and convergence rate and lithospheric age. Ruff and Kanamori's analysis indicates that the maximum energy magnitude is well fit by the following relationship.

$$M_w = -0.00889T + 0.134V + 7.96, \quad (1)$$

where T is the age of the subducting plate in millions of years, V is the convergence rate in centimeters/year, and the standard deviation of the observed M_w around the predicted value is 0.4.

Presence of active back-arc basins. In Figures 1 and 2, subduction zones with and without active back-arc basins are plotted as dots and circles, respectively. Subduction zones without active back-arc basins are clearly associated with the occurrence of large shallow subduction earthquakes. Thus, the absence of an active back-arc basins seems to be a good indication of relatively strong seismic coupling.

Depth of seismicity. Ruff and Kanamori (1980) show a good inverse correlation between the maximum depth of observed seismicity and the age of the subducted

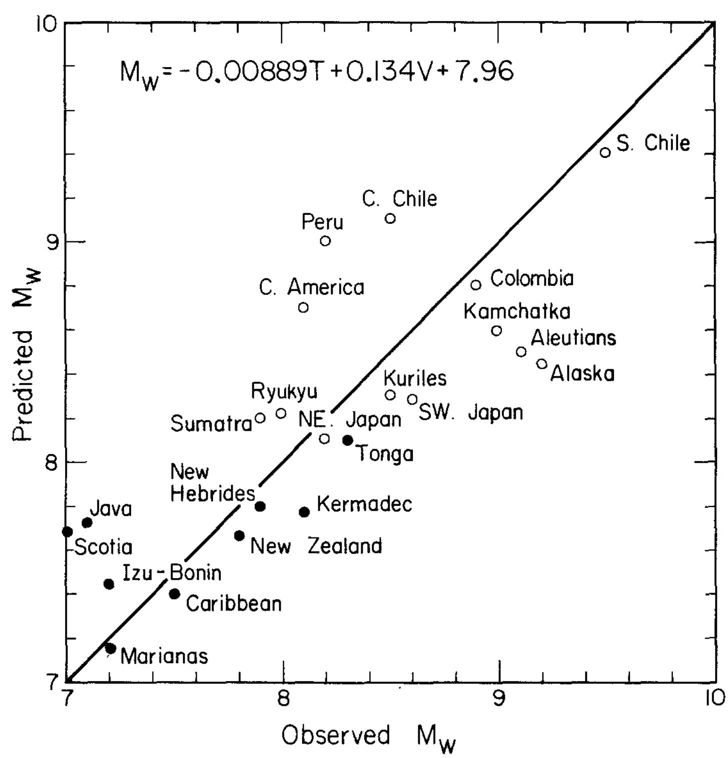

FIG. 2. Maximum observed energy magnitudes plotted against maximum energy magnitudes predicted from regression analysis shown in Figure 1. T is the age of the subducted plate in million years, and V is the convergence rate in centimeters/year. Dots and circles are subduction zones with and without active back-arc basins (modified from Kanamori, 1983).

plate, but the corresponding correlation between depth of seismicity and convergence rate is poor. Consequently, there is a weak correlation between the maximum depth of seismicity and the maximum observed earthquake size. However, 3 of the 4 subduction zones that have produced earthquakes of $M_w \geqq 9.0$ have maximum depths of seismicity of less than 200 km.

Depth of oceanic trench. Uyeda and Kanamori (1979) suggest that strongly coupled subduction zones are accompanied by shallow oceanic trenches, whereas weakly coupled subduction zones are accompanied by very deep oceanic trenches. Similarly, they conclude that free-air gravity anomalies tend to be larger for those trenches with weak seismic coupling.

Dip of Benioff-Wadati zone. Uyeda and Kanamori (1979) conclude that strong seismic coupling is usually associated with subduction zones having relatively gently dipping Benioff-Wadati zones. The uppermost part of strongly coupled subduction zones generally dips between 10° and 20°. They also conclude that strongly coupled subduction zones are characterized by the presence of well-developed fore-arc basins, which are believed to be accretionary prisms of sediments that develop on the landward wall of trenches. Furthermore, they note that this style of subduction is often accompanied by crustal uplift and compression in the overriding plate. These features are schematically shown in Figure 3.

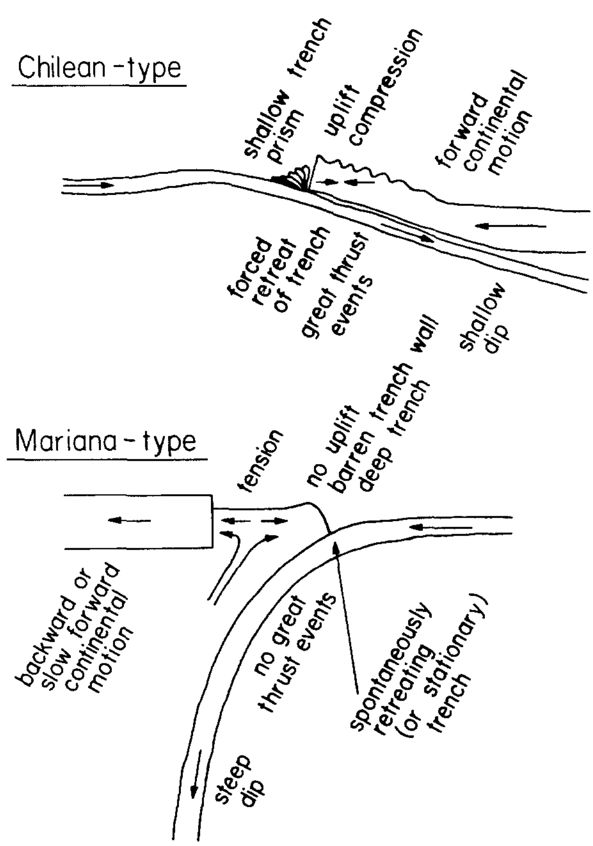

FIG. 3. Diagrams showing characteristics of strongly coupled (Chilean type) and weakly coupled (Mariana type) subduction zones (modified from Uyeda and Kanamori, 1979).

Topography of the subducted slab. Kelleher and McCann (1977) and Lay *et al.* (1982) both note that very large subduction earthquakes are more likely to occur in regions where the subducted plate has smooth topography. That is, the subduction of plates with transforms, ridges, or numerous seamounts is rarely associated with great earthquakes. Lay *et al.* (1982) suggest that the subduction of irregular topography results in heterogeneous strength distributions along the subduction zone and thereby inhibits the occurrence of earthquakes of large dimension.

Seismic quiescence. Although weakly coupled subduction zones may display a total absence of major earthquakes, they still have relatively high seismic activity at small magnitudes. Benioff-Wadati zones capable of truly great earthquakes, however, often show significant periods of extremely low seismicity (Lay *et al.*, 1982). This pattern may be somewhat analogous to the seismicity observed along the San Andreas fault in California. The central creeping portion of the fault is characterized by relatively high seismicity, but no large earthquakes. However, the portions of the fault that are capable of great earthquakes (1857 and 1906 breaks) are almost devoid of present-day seismicity.

THE JUAN DE FUCA SUBDUCTION ZONE

We have seen that there are systematic differences between subduction zones that are capable of great earthquakes and those that are not. The Juan de Fuca subduction zone has been ignored in the studies that established these differences. The Juan de Fuca subduction zone has been considered somewhat anomalous because there has been virtually no shallow thrust seismicity of the type we usually associate with active subduction zones. There are several possible explanations for this low level of seismicity: (1) the North American and Juan de Fuca plates are no longer converging; (2) the plates are converging but slip is accommodated aseismically; and (3) the northwestern United States is a major seismic gap that is locked and presently seismically quiescent, but that will fail in great earthquakes in the future. Each of these possibilities is discussed below.

Present-day convergence. The geometry of important plate boundaries and the seismicity in the Pacific Northwest are shown in Figure 4. Delaney *et al.* (1981) note that there appears to be 43 km of new oceanic crust formed on the Juan de Fuca ridge since the 700,000-yr-old Brunhes-Matuyama magnetic reversal, yielding a half-spreading-rate of about 3 cm/yr. The fact that the oldest crust found in the Juan de Fuca plate is on the order of 10 m.y. old (Atwater, 1970) indicates that subduction has occurred in the past. The average convergence rate for the past 5 m.y. has been estimated from magnetic reversal data to be 3.5 cm/yr by Riddihough (1977), 4.2 cm/yr by Chase *et al.* (1975), and 3.0 cm/yr by Nishimura *et al.* (1984).

Hyndman and Weichert (1983) show that historic seismicity can account for slip rates expected from magnetic reversal data on all plate boundaries between the Pacific plate and the North American plate except on the Juan de Fuca subduction zone. Furthermore, it seems difficult to concoct a model of plate motions which has 3.5 cm/yr slip rates on faults both north and south of the Juan de Fuca subduction zone, but with no convergence on the subduction zone itself. It thus appears that presently available evidence supports present-day plate convergence of 3 to 4 cm/yr across the Juan de Fuca subduction zone.

Physical features of the Juan de Fuca subduction zone and seismic coupling. The subducted part of the Juan de Fuca plate appears to be very young, probably between 10 and 15 m.y. old. We earlier said that subduction of young oceanic crust usually is associated with strong coupling. The subduction rate, 3 to 4 cm/yr, however, is not particularly high, and this rate does not in itself indicate particularly strong coupling. If we insert these values into equation (1), then we predict a maximum moment magnitude of $8.3 \pm .5$. This high value is supported by inspecting Figure 1. We see that strong coupling is associated with every subduction zone where the subducted plate is less than 40 m.y. old. The notion of strong seismic coupling along the Juan de Fuca subduction zone is further supported by the fact that there is clearly no active back-arc basin in the northwestern United States.

A cross section of seismicity in the Puget Sound region is shown in Figure 5. Although a clear Benioff-Wadati zone can be seen, seismicity deeper than 100 km has not been observed. The dip of the Benioff-Wadati zone, as defined by the axis of the trench and the pattern of seismicity beneath Puget Sound, is between 10°

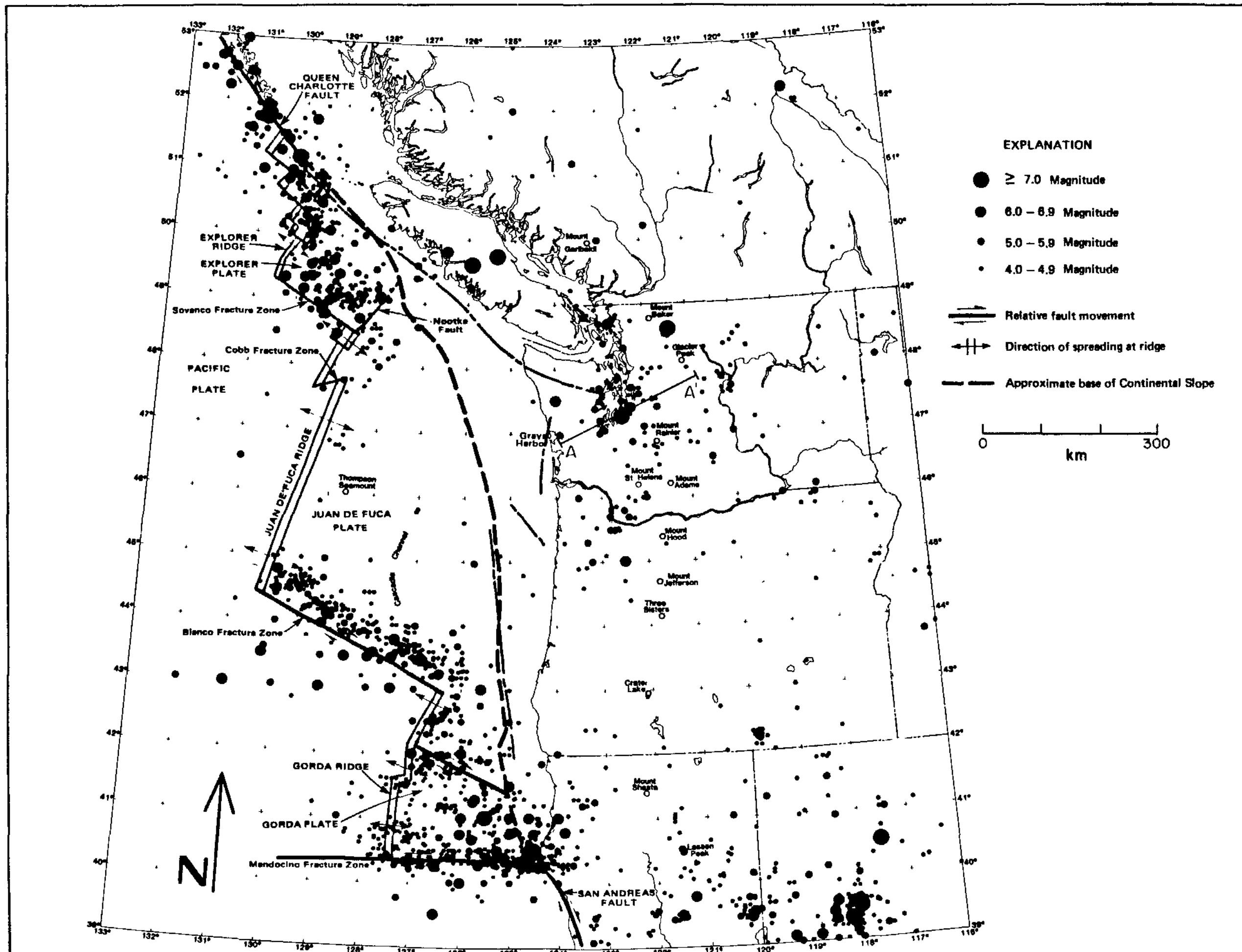

FIG. 4. Major tectonic features and associated seismicity of the Pacific Northwest (modified from Washington Public Power Supply System, 1983).

and 15°. Both of these features are characteristic of subduction zones with strong seismic coupling.

The oceanic trench off the coast of the Pacific Northwest is topographically a relatively subtle feature. Free-air gravity anomalies over the trench are also small compared to most other subduction-zone trenches (Riddihough, 1979) and much of the trench appears to be buried under a thick wedge of sediment (Scholl, 1974). Furthermore, the Juan de Fuca plate is topographically characterized as a smooth, featureless plain. All of these features further corroborate the interpretation that the Juan de Fuca subduction zone is strongly coupled and capable of large, shallow, thrust earthquakes.

One of the most striking features of the Juan de Fuca subduction zone is its present-day very low level of seismicity. There have been moderate events at depths of about 60 km under the Puget Sound in 1949 (M 7.2) and 1965 (M 6.5). However, these events appear to be on high-angle normal faults that occur within the

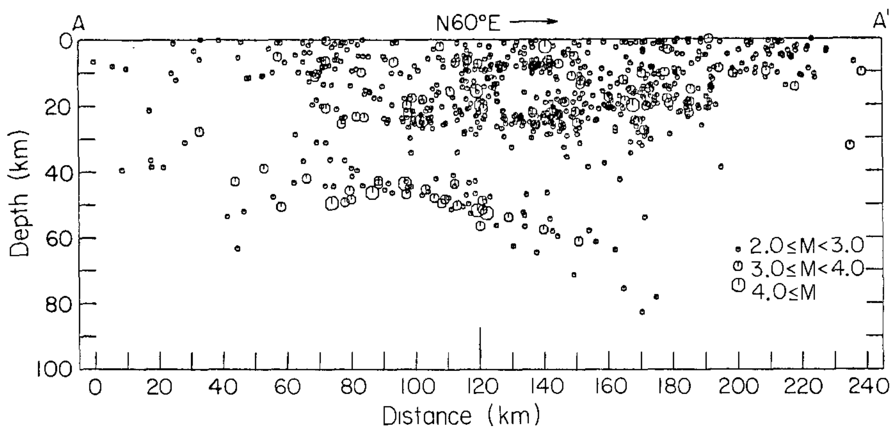

FIG. 5. Cross-section of seismic activity in the Puget Sound region from 1970 through 1978 (see Figure 4 for location of $A - A'$). Earthquakes with epicenters whose perpendicular distances from $A - A'$ is less than 150 km are included (modified from Crosson, 1980).

subducted slab (Wickens and Hodgson, 1967; Langston and Blum, 1977). The shallowest parts of the subduction zone are presently quiescent with respect to earthquakes of magnitude 4 or greater, and there is no historical record of a large shallow thrust earthquake anywhere along the subduction zone within the past 150 yr (Washington Public Power Supply System, 1983). This 500-km gap in seismic activity is one of the most remarkable to be found anywhere in the circum-Pacific seismic belt. As we noted earlier, the best examples of seismically quiescent plate boundaries are ones that have experienced great earthquakes but that could be considered as otherwise locked. If slip is occurring aseismically on the shallow part of the subduction zone, then this particular example would have to be considered unique.

Ando and Balazs (1979) discuss crustal uplift in the Pacific Northwest as inferred from leveling surveys in the period 1904 to 1974. They interpret crustal-uplift rates of about 2 mm/yr within 50 km of the coastline as being due to aseismic slip along the entire subduction plate boundary. However, this conclusion is contradictory to an interpretation by Savage *et al.* (1981) of horizontal strain as measured by laser ranging in the period 1972 to 1979. They report horizontal compression of 0.13

(± 0.02) microstrain/yr along a principal axis of compression directed N71°E. Weaver and Smith (1983) report northeast-southwest compression axes for earthquakes in the continental crust in southwestern Washington. Both Savage *et al.* (1981) and Weaver and Smith (1983) conclude that these observations are best modeled by coupling between the North American and Juan de Fuca plates which causes compressive strains oriented perpendicular to the subduction zone.

Conclusions

The Juan de Fuca and North American plates appear to be converging at a rate of between 3 and 4 cm/yr. The Juan de Fuca subduction zone shares many features with other subduction zones that are strongly coupled and capable of producing very large earthquakes. Although the shallow part of this subduction zone shows little present-day seismicity and no significant historical activity, we feel that there is sufficient evidence to warrant further study of the possibility of a great subduction zone earthquake in the Pacific Northwest.

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U.S. Geological Survey
California Institute of Technology
Pasadena, California 91125

Seismological Laboratory
California Institute of Technology
Pasadena, California 91125
Contribution No. 4070

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